INVESTIGATION OF NUCLEAR ACOUSTIC RESONANCE FOR THE NONDESTRUCTIVE DETERMINATION OF RESIDUAL STRESS

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ABSTRACT

Nuclear acoustic resonance has been studied in cylindrical specimens of polycrystalline aluminum deformed in compression and tension. The acoustic absorption lineshape is found to be asymmetric and dependent on the amount of deformation. Analysis of the signals in terms of an admixture of the real and imaginary parts of the nuclear susceptibility has been performed. The linewidth measured from the experimental signals varies with deformation exhibiting a minimum between twelve and fifteen percent strain.

INTRODUCTION

As is well known, residual stresses and internal strains play important roles in determining the service behavior of many materials, components and structures. As such, the detection and quantitative characterization of residual stresses and internal strains are crucial factors in the rational assessment of the serviceability of structural materials. The present program was initiated in response to the important need for a practical method of making residual stress measurements in nonferromagnetic materials. One of the methods under investigation is nuclear acoustic resonance (NAR) in which changes in acoustic absorption due to nuclear magnetic resonance (NMR) are measured. The advantage of this approach for NDE over the conventional inductive NMR method is that the acoustic approach is sensitive to the interior of bulk metal specimens whereas the inductive approach is limited to the electromagnetic skin depth which is typically only 10 to 100 microns at the radiofrequencies usually employed.

The effect of residual stress and internal strain on the nuclear resonance signal (either inductive or acoustic) is associated with the interaction between the nuclear quadrupole moment and the electric field gradient (EFG) determined by other ions and electrons. For cubic symmetry the EFG normally vanishes, however, lattice distortion associated with stress-strain fields can produce EFG's in nominally cubic materials (Figs. 1 and 2). The resulting quadrupole interaction perturbs the magnetic energy levels thus modifying the detected nuclear resonance signal.

EXPERIMENTAL

The NAR approach, illustrated in Fig. 3, involves coupling ultrasonically to a specimen which is subjected to a static magnetic field. In the experiments reported here, a continuous wave (cw) transmission method was used.[1] Acoustic standing waves of approximately 60 MHz were established by means of a transducer bonded to one end of a cylindrical specimen. Changes in acoustic attenuation as the applied magnetic field was slowly swept through the resonance condition were measured by means of a second transducer bonded to the other end of the specimen. To enhance the signal-to-noise ratio, synchronous detection and signal averaging were used. Experimental conditions are detailed in Table I.

RESULTS

Typical NAR signals obtained from aluminum specimens subjected to various amounts of compressive deformation are shown in Fig. 4. The indicated strain values were determined from the changes in specimen length after deformation. The displayed NAR signals are the first derivatives of the acoustic absorption. The amplitudes of these signals cannot be directly compared since this parameter is affected by the bonding characteristics of the transducers among other factors. However, all of the detected NAR signals were found to be asymmetric in agreement with previously reported results for single crystal aluminum.[2] This asymmetry has been shown both experimentally[3] and theoretically[4] to be associated with an admixture of χ' and χ'' (the real and imaginary parts, respectively, of the complex nuclear susceptibility) according to the following expression for the resonant acoustic absorption

$$\Delta\alpha \propto [(1 - \beta^2)\chi'' - 2\beta\chi'] \qquad (1)$$

where β is a factor depending on the acoustic velocity and electrical conductivity.

The relative amplitudes of the peaks of the NAR first derivatives are a measure of the asymmetry of the acoustic absorption lineshape and can be used to determine the percentages of χ' and χ'' based on the assumption of a Gaussian lineshape. The amounts of χ'' determined in this way are listed in the second column of Table II, while similar results obtained by analyzing the experimental acoustic absorption second derivatives are listed in the third column. No consistent variation of χ'' with strain was found and except for the undeformed specimen, the χ'' components computed from the two derivatives are quite different. The implication of these results is that the assumption of a Gaussian lineshape for acoustic absorption from deformed aluminum may not be valid. Indeed, comparisons between the experimental signals and Gaussian lineshapes (shown by open circles in Fig. 4) show that the deviation from a Gaussian lineshape increases with increasing deformation.

In addition to determining χ'', the NAR signals from deformed aluminum were analyzed to obtain information on the acoustic absorption linewidth. The linewidths determined by measuring the peak-to-peak separations of the experimentally recorded signals are tabulated in columns 2 and 3 of Table III for the first and second derivatives, respectively. Determined in this way, the experimental linewidth initially decreases with plastic deformation and then increases for strains greater than approximately 15 percent. Although a change in resonance linewidth is expected for quadrupole perturbed energy levels, the results presented here are difficult to interpret analytically since the variation of the admixture of χ' and χ'' with strain also affects the linewidth. Thus for comparison with theory, the linewidth in terms of the χ'' component must be extracted from the experimental NAR signals.

Interesting results have been obtained indicating that the acoustic absorption lineshape for the deformed aluminum specimens is dependent on the frequency used to modulate the static magnetic field for synchronous detection. As shown in Fig. 5, for a lightly deformed specimen (5% tensile strain), the NAR lineshape is essentially independent of modulation frequency (results were obtained in the 25-100 Hz range) whereas for a highly deformed specimen (25% tensile strain) the lineshape changes substantially with modulation frequency. In fact, as the modulation frequency is decreased from 100 Hz to 35 Hz, the lineshape for the 25% tensile strain specimen changes from approximately 50% or 60% χ'' to approximately 20% χ''. Since the modulation frequency determines the depth of penetration of the magnetic field into the specimen, a possible interpretation of these results is that the change in lineshape observed for the 25% deformed specimen may be associated with inhomogeneous deformation existing in this specimen.

CONCLUSIONS

As a consequence of the results obtained to date, the following conclusions are reached:

(1) Nuclear acoustic resonance signals observed in polycrystalline aluminum are quantitavely similar to NAR signals in single crystal aluminum.

(2) The NAR signals are asymmetric due to an admixture of χ' and χ''.

(3) The NAR linewidth and admixture of χ' and χ'' vary with plastic deformation.

(4) The NAR lineshape for plastically deformed aluminum does not fit a Gaussian function.

(5) The effect of modulation frequency on lineshape depends on the amount of plastic deformation.

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Table I.
Experimental Conditions

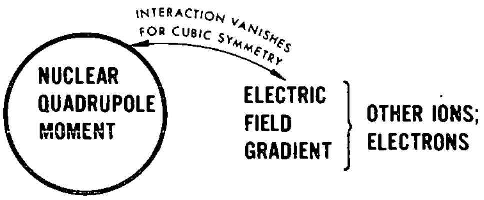
SPECIMENS:	99.999% PURE POLYCRYSTALLINE ALUMINUM
CYLINDERS:	1/2-IN. LONG BY 1/2-IN. DIAMETER
FREQUENCY:	60 MHz
MAGNETIC FIELD:	54 kG
TEMPERATURE:	4.2°K & 65°K
ACOUSTIC MODE:	SHEAR

Table II.
The Imaginary Component, χ'', of the Complex Nuclear Susceptibility for Plastically Deformed Aluminum Based on Measurements of Experimental Curves and Gaussian Lineshape Assumption

Strain (%)	χ'' (%) First Derivative	χ'' (%) Second Derivative
0	84	89
4.8	49	88
9.8	82	63
14.9	53	71
19.8	48	77
25.0	66	51

Table III.
The Acoustic Absorption Linewidth for Plastically Deformed Aluminum Measured from Experimental Curves

Strain (%)	Linewidth (Gauss) First Derivative	Linewidth (Gauss) Second Derivative
0	9.3	10.5
4.8	8.0	11.3
9.8	7.3	9.7
14.9	7.2	8.5
19.8	8.9	9.3
25.0	8.0	10.5



EFG IN CUBIC CRYSTALS CAUSED BY:

1. Stress-Strain Fields Produced by External Loads or Lattice Defects
2. Charge Difference Between Point Defects and Host Ions
3. Redistribution of Conduction Electrons Around a Defect in the Case of Metals

Fig. 1. Schematic Illustration of Nuclear Quadrupole Interaction

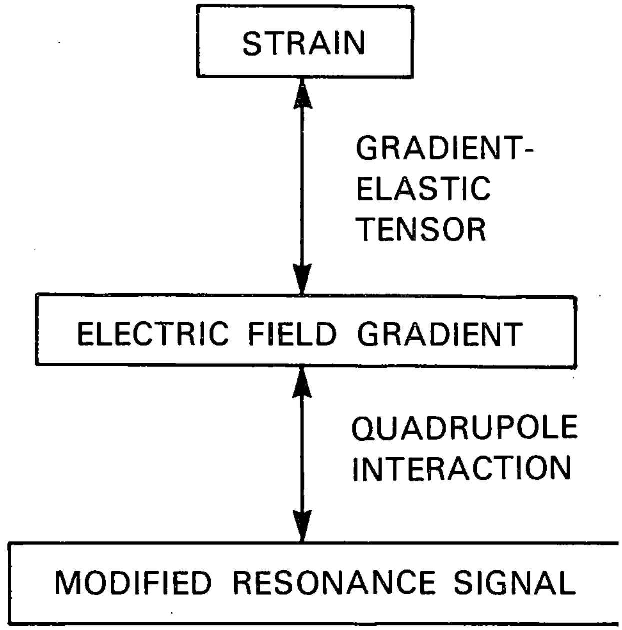


Fig. 2. Relationship Between Lattice Strain and Nuclear Acoustic Resonance

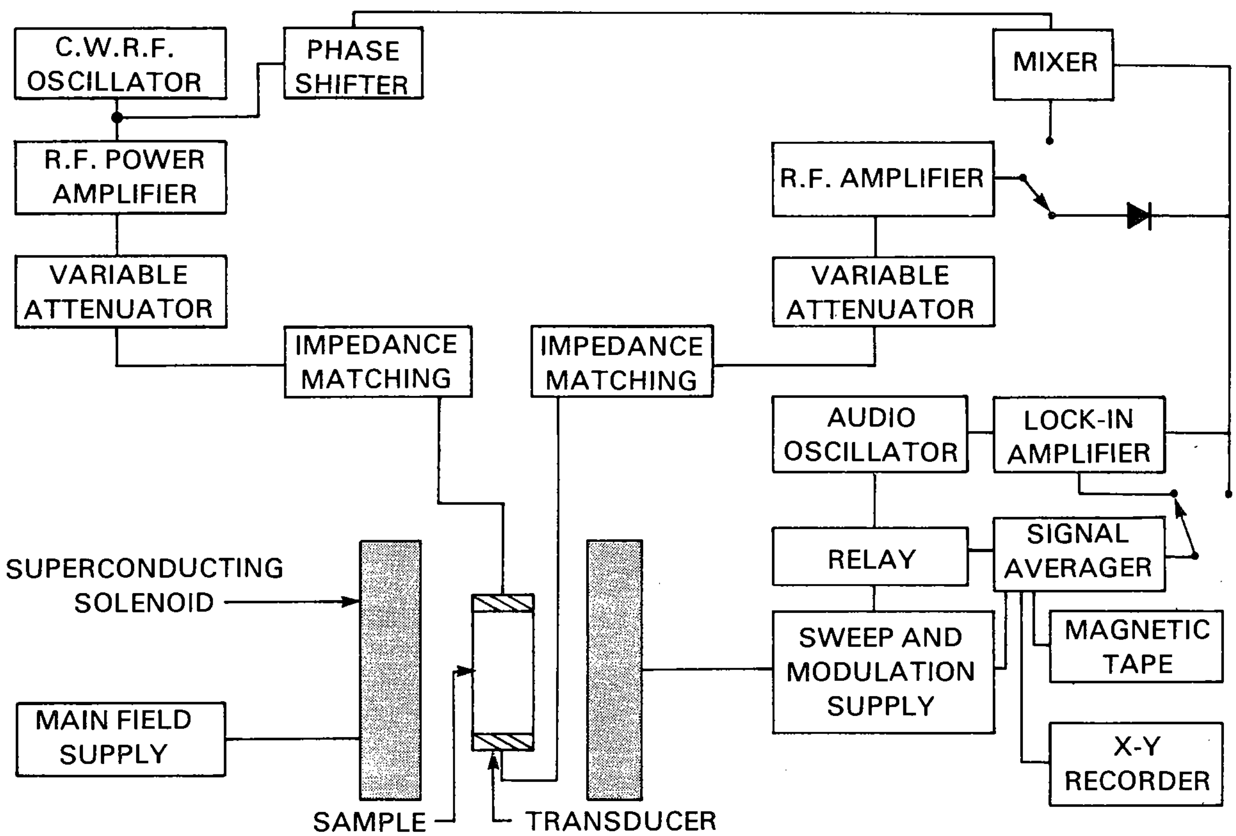


Fig. 3. Block Diagram of Nuclear Acoustic Resonance Approach

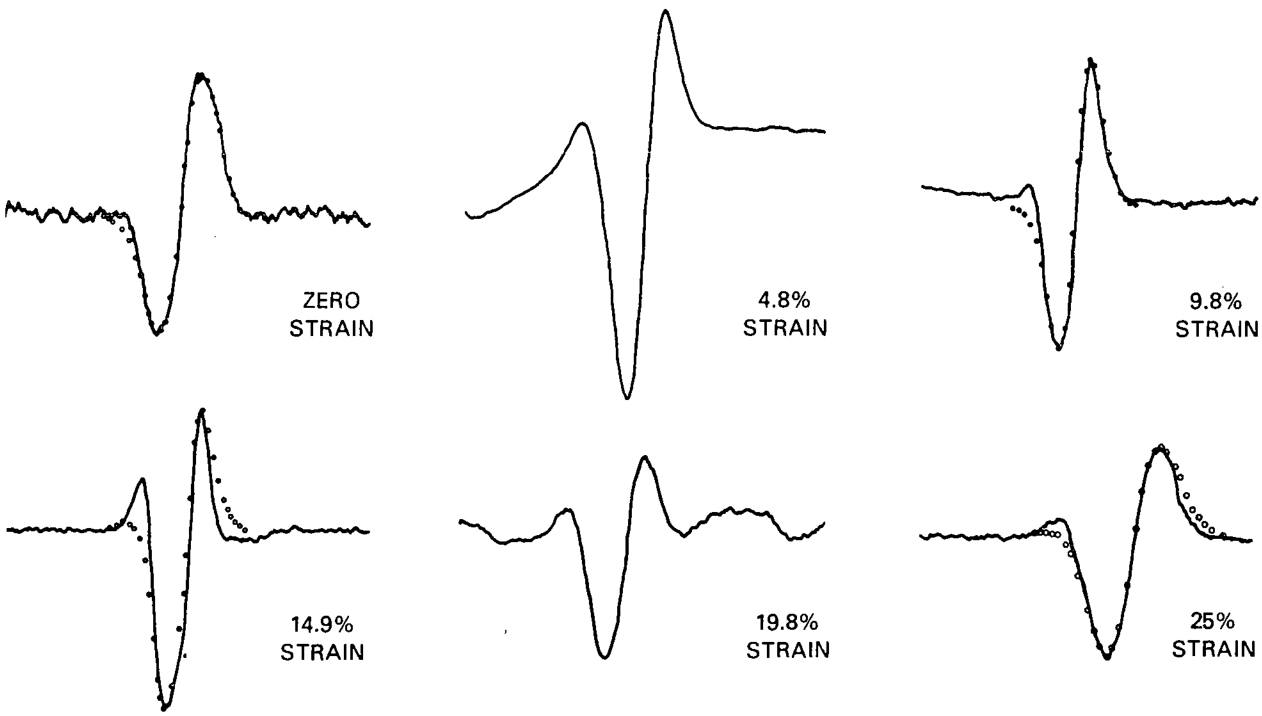


Fig. 4. Dependence of Aluminum Acoustic Absorption First Derivative on Compressive Strain

Open Circles Represent the Gaussian Lineshape; The Solid Line Shows the Experimental NAR Signals

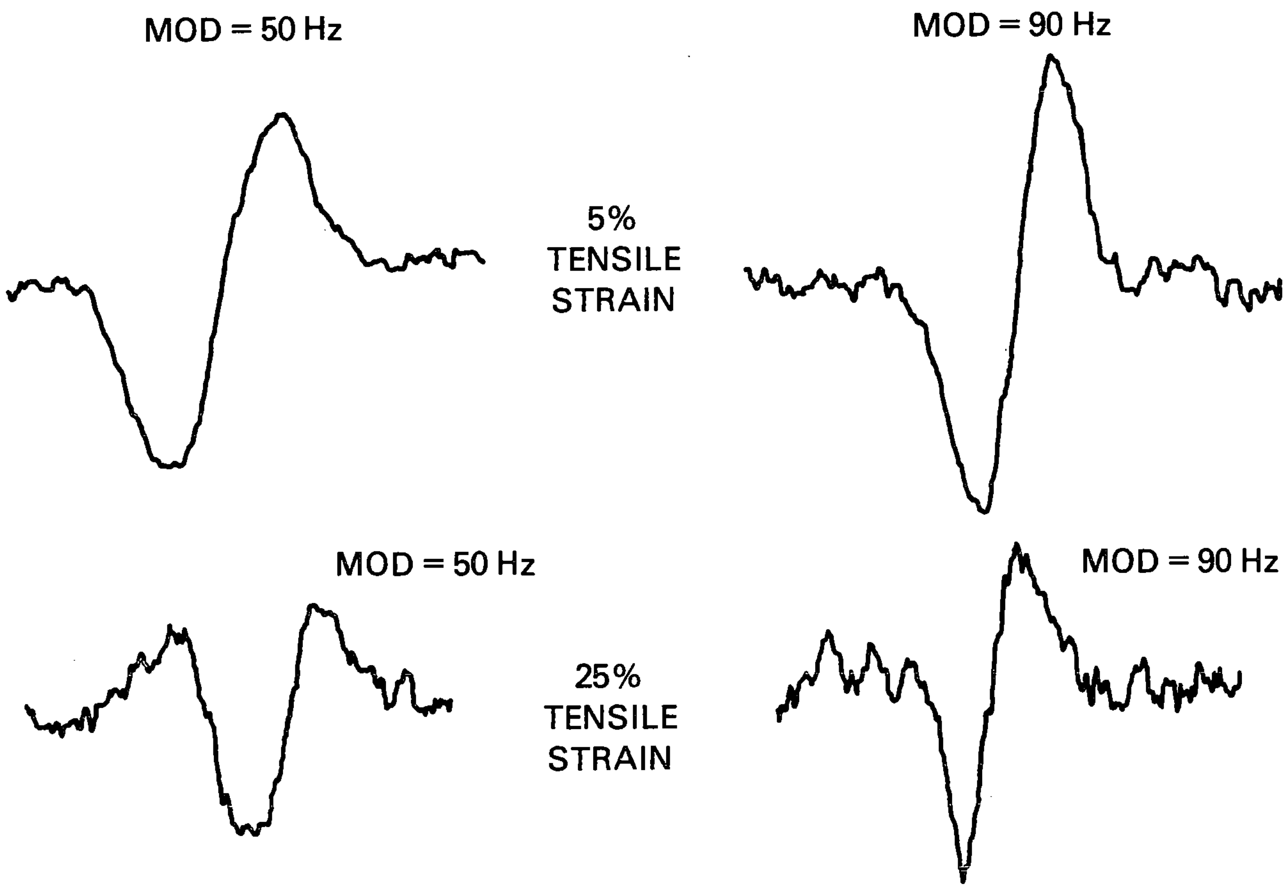


Fig. 5. Effect of Modulation Frequency on NAR Lineshape as a Function of Plastic Deformation in Polycrystalline Aluminum